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Robust Mesh Insensitive Structural Stress Method for Fatigue Analysis of Welded Structures

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Abstract

The design of welded structures and careful fatigue design evaluation is especially important in structural design since the stress concentrations at the welds have significant impact on the overall fatigue lives of the structures. Currently, the nominal stress or hot spot stress methods are widely used in the field for fatigue design evaluation. However, design based on these methods requires constructing separate S-N curves from the fatigue testing based on the joint geometry, loading, thickness, etc. It is also difficult to evaluate the fatigue performance using finite element analysis, where the calculated stress can vary according to element size, type, etc. To overcome these challenges, Battelle has developed a novel, mesh insensitive structural stress method (Verity®). The stresses are calculated using the balanced nodal forces and moments obtained at the weld toe location from the finite element solutions. Working with industry partners, Battelle has also developed a unified master S-N curve that combines the effects of joint geometry, loading modes and thicknesses. Battelle's structural stress procedure has been adopted as design weld fatigue codes by ASME Sec. VIII Div. 2 (ASME Boiler and Pressure Vessel Code) and API 579/ASME FFS-1 (Fitness-for-Service Evaluation). As a case study, the fatigue life prediction of a rectangular hollow section joint using a new structural stress method is presented in this paper.

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Keywords: Structural stress; welded structures; verity®; fatigue life

1. Introduction

A mesh-insensitive structural stress method has been developed by Battelle researchers and has been commercialized to industries to predict the fatigue behavior of welded joints [1-3]. The Battelle structural stress based master S-N curve has been constructed for weld toe failure by incorporating more than 800 well documented fatigue test results. This procedure has been implemented for weld fatigue design by 2007 ASME Sec. VIII Div.2 [4] and API 579-1/ASME FFS-1 2007 [5]. The commercial version of this method (Verity®) is available in one of the modules in Fe-Safe™ software package [6].

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This paper provides the details of the structural stress approach and life prediction procedure applied to rectangular hollow section joint.

2. Mesh insensitive structural stress method

The mesh-insensitive structural stress method [1-3] is based on equilibrium-based decomposition of an arbitrary stress state at a location of interest such as at weld toe (Fig. 1a) into an equilibrium equivalent structural stress part (Fig. 1b) and a self-equilibrating notch-stress part (Fig. 1c) from a displacement based finite element solution. The structural stress part (σ_s) is characterized as

$$\sigma_s = \sigma_m + \sigma_b \tag{1}$$

which represents a simple stress state in the form of membrane and bending components that satisfies the equilibrium at the location with external loading. In Fig. 1, $\sigma_x(y)$ and $\tau(y)$ are normal and transverse shear stress under axial force P in x direction, σ_m is the membrane stress component, σ_b is the bending stress component, and t represents the plate thickness. The transverse shear stress (τ_m) can be calculated based on the local transverse shear stress ($\tau(y)$) distribution.

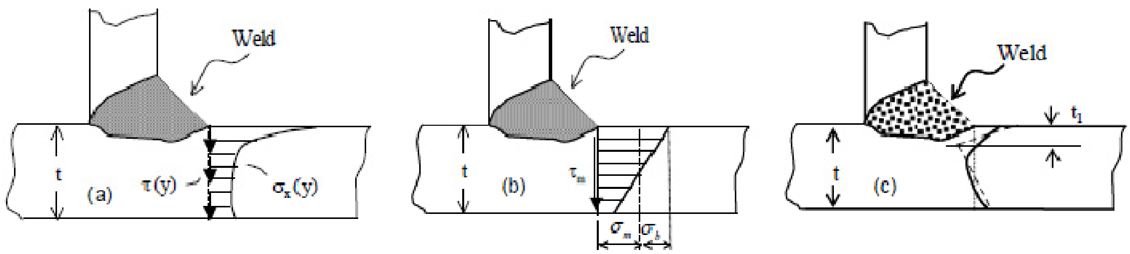

Fig. 1. Through-thickness structural stress definition in welded joints: (a) local stresses from FE model; (b) structural stress or far-field stress; (c) self-equilibrating stress.

To achieve a good mesh-insensitivity for analyzing welded joints within the context of displacement-based finite element methods, the structural stress arguments can be most effectively implemented by using balanced nodal forces and moments in shell, plate and 3D finite element models, as shown in Fig. 2. Then, the structural stress components at each node along the weld can be calculated as:

$$\sigma_s = \sigma_m + \sigma_b = \frac{f_{y'}}{t} - \frac{6m_{x'}}{t^2} \tag{2}$$

where $f_{y'}$ is line force in the direction of y', and $m_{x'}$ is line moment about x' in a local coordinate system as shown in Fig. 2. The detail formulation, calculation procedures as well as calculation examples are given in previous publications [1-3].

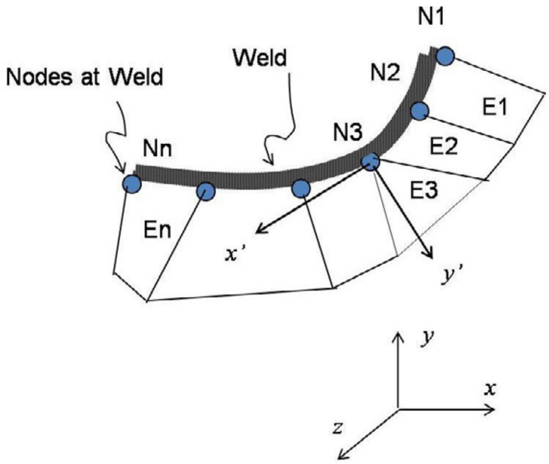

Fig. 2. Robust structural stress calculation procedures for curved weld with distorted mesh using shell element models.

2.1. Master S-N curve approach

The master S-N curve approach is documented in a number of publications by Battelle researchers [2]. Based on a two stage crack growth model, an equivalent structural stress parameter can be derived using the fracture mechanics principles.

2.1.1. Equivalent structural stress parameter (ΔS_S)

Based on a two stage crack growth model, an equivalent structural stress parameter derived using fracture mechanics principles has been shown to consolidate all plate joint fatigue data relevant to steel structures onto a narrow band, referred to as the master S-N curve. The equivalent structural stress range parameter (ΔS_S) is defined as:

$$\Delta S_s = \frac{\Delta\sigma_s}{t^{\frac{2-m}{2m}} \cdot I(r)^{\frac{1}{m}}} \tag{3}$$

$\Delta\sigma_S$ represents the structural stress range, $I(r)^{\frac{1}{m}}$ is a dimensionless polynomial function of the bending ratio r (under load controlled conditions), and m is crack propagation exponent in conventional Paris law, taking on a value of about 3.6 [2].

$$I(r)^{\frac{1}{m}} = 0.0011 \cdot r^6 + 0.0767 \cdot r^5 - 0.0988 \cdot r^4 + 0.0946 \cdot r^3 + 0.0221 \cdot r^2 + 0.014 \cdot r + 1.2223 \tag{4}$$

$$where,\ r = \frac{|\Delta\sigma_b|}{|\Delta\sigma_m| + |\Delta\sigma_b|} \tag{5}$$

For details to derive the I(r) function see reference [2]. It should be emphasized that the equivalent structural stress parameter described in eq. (3) can capture the effects of stress concentration ($\Delta\sigma_S$), plate thickness (t), and loading mode effects (r) on fatigue behavior of welded components. The master S-N curve in Fig. 3 in the form of the mean and standard deviations can be expressed as

$$\Delta S_S = C\ X\ N^h \tag{6}$$

where C is material constant and h represents the negative slope of the master S-N curve in Fig. 3. By performing regression analysis with respect to the cycles to failure, Table 1 summarizes the statistical parameters of the master S-N curve defined in eq. (6) in terms of the mean, $\pm 2\sigma$ and $\pm 3\sigma$. Note that the stress units are in MPa and length units are in mm. The curves illustrated by $\pm 2\sigma$ represent approximately 95% prediction intervals.

Table 1. Master S-N curve parameters [2]

Statistical basis	C	h
Mean	19930.2	
$+2\sigma$ (upper 95%)	28626.5	
-2σ (lower 95%)	13875.7	-0.32
$+3\sigma$ (upper 99%)	34308.1	
-3σ (upper 99%)	11577.9	

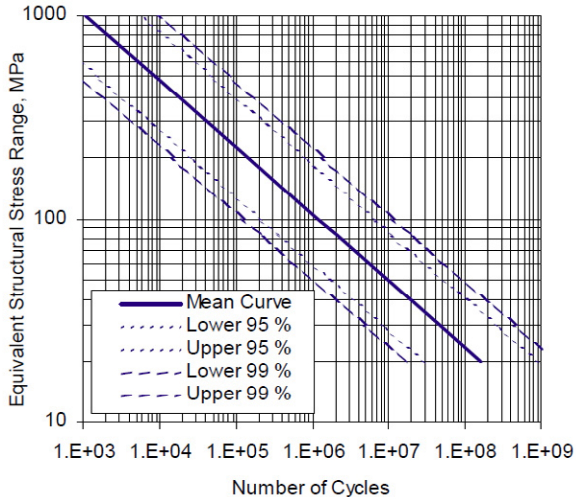

Fig. 3. Master S-N curve [2].

3. Case study - life prediction of a rectangular hollow section joint

The fatigue life prediction of a rectangular hollow section joint is presented as a case study. The specimen is made of a 4” x 4” (101.6 x 101.6 mm) section and a 2” x 6’’ (50.8 x 152.4 mm) section as shown in Fig. 4 [7-8]. The wall thickness and the weld size are both 0.312” (7.9 mm). A maximum load of 4000 lb (17.8 kN) was applied at the end of the 4”x4” tube through the rigid plate at 12.5” (317.5 mm) above the center of the 4”x4” cross section and the loading was fully reversed (loading ratio, R= -1). The failure location was given by the arrow on the specimen as shown in Fig. 5a, and the number of cycles to failure (mean value) was 75,000 cycles with scattering between 20,000 to 200,000 cycles [8].

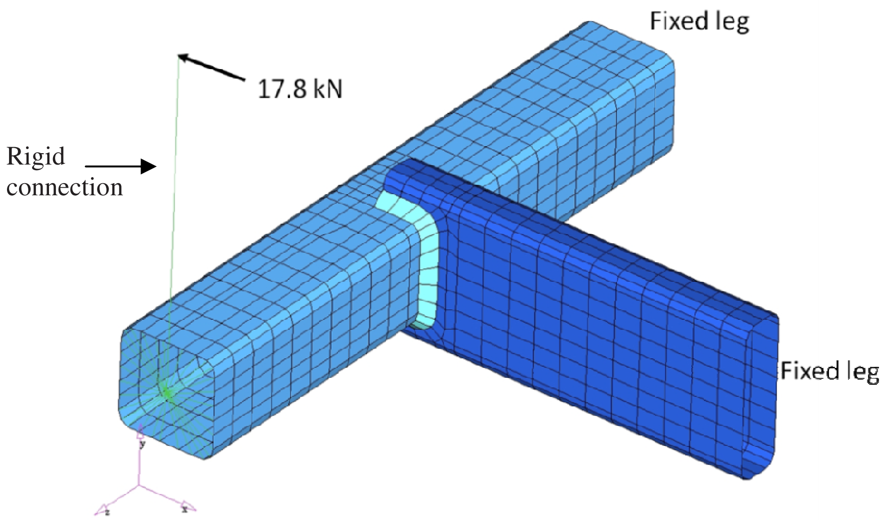

Fig. 4 Finite element shell model of rectangular hollow joint specimen with loading and boundary conditions

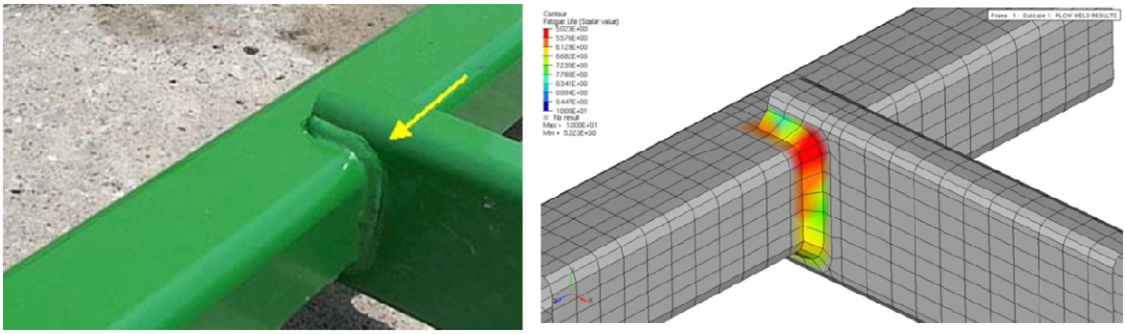

Fig. 5. Comparison of actual fatigue test result with simulation result:
(a) Crack location [8] ; (b) Verity® life contour plot.

In order to calculate the life of component using eq. (6) and Table 1, the equivalent structural stress needs to be calculated based on eqs. (2) to (5). The balanced nodal forces and moments were directly extracted from the finite element analysis at each nodal point along the weld line. Then the structural stress range ($\Delta\sigma_s$) using eq. 3 was calculated for each weld line. Lives for the each curve in Table 1 and Fig. 3 are listed in Table 2. The mean life 74,400 cycles is in excellent agreement with the experimental results (approximately 75,000) cycles.

Table 2 Fatigue life prediction from Master S-N curve

Statistical basis	Fatigue life at R = -1
Mean curve	7.44E+04
+2σ	4.12E+05
-2σ	1.34E04
+3σ	7.12E+05
-3σ	7.77E+03

4. Conclusion

In this paper, the capabilities of Battelle's mesh insensitive structural stress method (Verity®) have been demonstrated through the tubular joint specimen. This method can adequately capture the failure location and provide a good life prediction for welded components regardless of their joint geometry, loading mode and plate thickness. Further, the Verity® method can simplify fatigue analysis procedures for welded components and significantly reduce testing requirements.

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